Defense Technical Information Center Compilation Part Notice

ADP014938

TITLE: Transport Properties of Dense Laser Plasmas

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: International Conference on Phenomena in Ionized Gases [26th] Held in Greifswald, Germany on 15-20 July 2003. Proceedings, Volume 4

To order the complete compilation report, use: ADA421147

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP014936 thru ADP015049

Transport Properties of Dense Laser Plasmas

M. Schlanges[1], Th. Bornath[2], P. Hilse[1], D. Kremp[2]
[1] Institut für Physik, Ernst-Moritz-Arndt-Universität Greifswald, Domstrasse 10a, 17487 Greifswald, Germany
[2] Fachbereich Physik, Universität Rostock, Universitätsplatz 3, 18051 Rostock, Germany

Generalized kinetic equations are used to investigate transport properties of dense plasmas in strong laser fields. Quantum statistical expressions are derived for, e.g., the collision frequency to account for nonlinear field phenomena as well as strong correlation effects. The influence of these effects on collisional absorption is discussed.

1. Introduction

The impressive progress in laser technology makes femtosecond laser pulses of very high intensity available in laboratory experiments. If solid targets are irradiated by such laser pulses, dense plasmas can be created relevant for astrophysics and inertial confinement fusion. To understand transport properties of intense laser–plasma interaction, a theoretical modelling of dense nonideal plasmas in strong laser fields is needed.

One of the important mechanisms of energy deposition is inverse bremsstrahlung, i.e., laser light absorption via collisional processes between the plasma particles. In strongly ionized plasmas, this absorption process is essentially governed by the electron–ion interaction usually described in terms of the electron–ion collision frequency.

A lot of work has been done up to now to consider the electron–ion collision frequeny and the dynamic conductivity, respectively, for laser plasmas under different conditions. The well-known classical theories were developed in, e.g., [1, 2, 3]. Basic equations of a rigorous quantum kinetic approach to laser plasmas were derived in Ref. [4].

We consider a fully ionized plasma under the influence of a spatially homogeneous electric field. Starting point is a generalized kinetic equation for the gauge invariant Wigner distribution function which follows from the time diagonal Kadanoff–Baym equation. The central quantity in the collision term is the self energy function. Powerful schemes are available to determine appropriate approximations for the self–energy function taking into account nonlinear field dependence as well as many–body and quantum effects relevant for high density plasmas.

2. Collisional absorption

As we are interested here in the collisional absorption by the plasma, it is obvious to start from the balance equation for the energy and for the electrical current resulting from the kinetic equation. As the collison integral is a non–Markovian one, the energy balance reads

$$\frac{dW^{\mathrm{kin}}}{dt} + \frac{dW^{\mathrm{pot}}}{dt} = \mathbf{j}\cdot\mathbf{E}\,, \tag{1}$$

i.e., the change of the total energy of the plasma particles is equal to $\mathbf{j}\cdot\mathbf{E}$ that is in turn the energy loss of the electromagnetic field due to Poynting's theorem.

For the calculation of the collisional absorption, we start from the general balance equation for the current density of species a. It follows

$$\begin{aligned}&\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{j}_a(t) - n_a\frac{e_a^2}{m_a}\,\mathbf{E}(t)\\ &= \sum_{b\neq a}\int\frac{d^3q}{(2\pi\hbar)^3}\,\frac{e_a\mathbf{q}}{m_a}\,V_{ab}(q)\,L_{ab}^{<}(\mathbf{q};t,t)\,,\end{aligned} \tag{2}$$

where $V_{ab}(q)$ is the Fourier transform of the Coulomb potential. The collision term is now expressed by the correlation function of the density fluctuations given by $i\hbar L_{ab}^{<}(t,t') = \langle\delta\rho_b(t')\delta\rho_a(t)\rangle$. For this function an appropriate approximation has to be found. In Born approximation the current can be expressed by the Lindhard dielectric function. For a harmonic field $\mathbf{E} = \mathbf{E}_0\cos\omega t$, the field dependence is described by a Fourier series in terms of Bessel functions. This scheme allows to investigate the current density and the energy dissipation in dense weakly nonideal laser plasmas including dynamic screening, quantum effects as well as nonlinear field phenomena such as higher hamonics and multiphoton processes. The details of the investigation are presented in Ref. [6].

To include strong correlations one has to go beyond the Born approximation. An approximation which accounts for strong correlations in the ion and electron subsystems, we derived in Ref. [7]. Now, the resulting expression for the current is given in terms of dynamical structure factors and the exact density response functions. Again, the field dependence is described by a Bessel function expansion which causes the nonlinear field effects mentioned above. An important quantity is the cycle averaged dissipation of energy $\langle\mathbf{j}\cdot\mathbf{E}\rangle$. In the case of high-frequency fields, we get

$$\begin{aligned}\langle\mathbf{j}\cdot\mathbf{E}\rangle &= \int\frac{d^3q}{(2\pi\hbar)^3}\frac{\epsilon_0 q^2}{\hbar^2 e_e^2}\,V_{ei}^2(q)\,n_i\,S_{ii}(\mathbf{q})\\ &\times\sum_{n=-\infty}^{\infty} n\omega\,J_n^2\left(\frac{\mathbf{q}\cdot\mathbf{v}_0}{\hbar\omega}\right)\mathrm{Im}\,\frac{1}{\varepsilon_e(\mathbf{q};-n\omega)}\,,\end{aligned} \tag{3}$$

with $\varepsilon_e^{-1}(\mathbf{q};\omega) = 1 + (\hbar^2 e_e^2)/(\epsilon_0 q^2)\,\mathcal{L}_{ee}^R(\mathbf{q};\omega)$ being the dielectric function with the density reponse function of the electron gas $\mathcal{L}_{ee}(\mathbf{q})$. As high frequency fields are considered the static ion–ion structure factor $S_{ii}(\mathbf{q})$ appears in (3) instead of the dynamical one. Furthermore, J_n is the Bessel function of nth order and $v_0 = eE_0/m_e\omega$ is the so-called quiver velocity.

Often the electron–ion collision frequency ν_{ei} is discussed which is defined for the high-frequency case by (ω_p - plasma frequency)

$$\nu_{ei} = \frac{\omega^2}{\omega_p^2} \frac{\langle \mathbf{j} \cdot \mathbf{E} \rangle}{\langle \epsilon_0 \mathbf{E}^2 \rangle}. \tag{4}$$

Using the Lindhard dielectric function and neglecting ion–ion correlations (S_{ii}=1), the results follow we derived in Ref. [6]. Those results have a similar form as that of the nonlinear Dawson-Oberman model [1]. However, in our formula, the dielectric function is given by the quantum Lindhard form, whereas the dielectric theory of Decker et al. leads to the classical Vlasov dielectric function.

3. Numerical results

We compare the results obtained in the frame work of the quantum kinetic approach with the results of the classical theories. In Fig. 1 the collision frequency is shown as a function of the coupling parameter $\Gamma = (e^2/4\pi\varepsilon_0)/dk_BT$ with $d = (4\pi n/3)^{-1/3}$ for a strong field ($v_0/v_{th} > 1$). Results using the Lindhard dielectric function and $S_{ii}(\mathbf{q}) = 1$ are given by the upper curve. In the case of static screening the collision frequency is reduced.

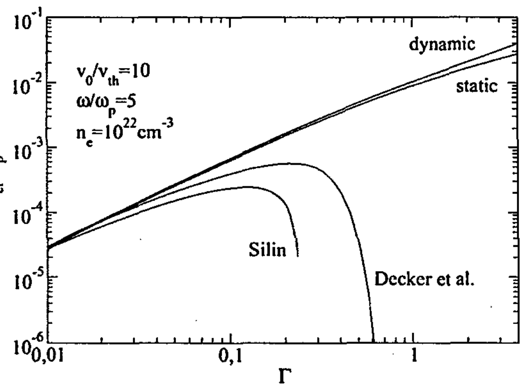

Fig. 1: Electron–ion collision frequency as a function of the coupling parameter Γ for a hydrogen plasma in a strong laser field. Comparison is given with the theory of Decker et al. and with the asymptotic formula of Silin.

For small values of Γ (weakly nonideal plasma), the classical dielectric theory of Decker et al. [1] and the classical asymptotic formula by Silin [2] give almost the same results. However, with increasing Γ, the classical curves show a sharp drop down. This behaviour results from a cutoff procedure at large wave numbers used in the classical theories. Such a cutoff is avoided in our approach automatically, and the range of applicability is extended to higher values of the coupling parameter.

As discussed above, the expression (3) generalizes the results to dense quantum plasmas including strong correlation effects.

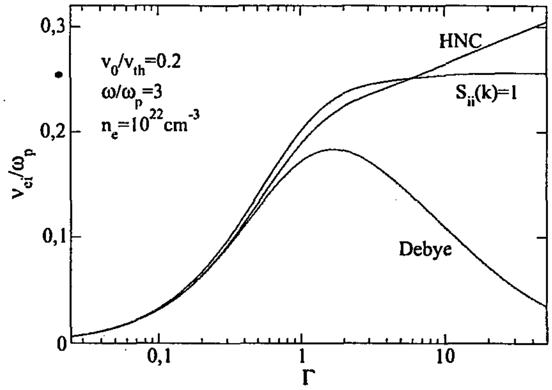

Fig. 2: Electron–ion collision frequancy as a function of the coupling parameter Γ. Ion structure factors in different approximations: HNC and Debye.

Let us consider the influence of the ion–ion correlations. In Fig. 2 the collision frequency is shown using different approximations for the static ion-ion structur factor S_{ii} (in the dielectric function, we included local field corrections [7]). Here $v_0/v_{th} = 0.2$, i.e. a smaller field strength is considered. Inclusion of the structure factor in hypernetted chain (HNC) approximation decreases the collision frequency for small and moderate coupling up to $\Gamma \approx 5$ whereas an increasing behaviour follows for high values of the coupling parameter. As expected, the Debye approximation can be applied only for weak coupling. Good agreement with data obtained by simulations can be found in the range $\Gamma < 1$ [6].

References

[1] C. Oberman, A. Ron, and J. Dawson, Phys. Fluids **5**, 1514 (1962); C.D. Decker, W.B. Mori, J.M. Dawson, and T. Katsouleas, Phys. Plasmas **1** (1994) 4043.

[2] V.P. Silin, Zh. Eksp. Teor. Fiz. **47** (1964) 2254.

[3] Yu.L. Klimontovich, *Kinetic Theory of Nonideal Gases and Nonideal Plasmas* (Nauka, Moscow 1975 (russ.)).

[4] D. Kremp, Th. Bornath, M. Bonitz and M. Schlanges, Phys. Rev. **E 60** (1999) 4725.

[5] M. Schlanges, Th. Bornath, D. Kremp, M. Bonitz, P. Hilse, J. Phys. IV France **10** (2000) Pr5–323.

[6] Th. Bornath, M. Schlanges, P. Hilse, D. Kremp, Phys. Rev. E **64** (2001) 026414.

[7] Th. Bornath, M. Schlanges, P. Hilse, D. Kremp, J. Phys. A, accepted.